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# Germany's "No" to carbon capture and storage: Just a question of lacking acceptance?

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## HIGHLIGHTS

- Carbon capture and storage being regarded as option to mitigate climate change loses support.
- Sustainability indicators are not the only ones stakeholders are interested in.
- Even factors distinct from sustainably indicators shows a gloomy future for CCS.
- A more intensive use of renewables will be more beneficial from an economic and social point of view.

## ARTICLE INFO

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## ABSTRACT

Carbon capture and storage (CCS) is frequently regarded as a promising approach to mitigate global warming. Yet, by and by CCS is losing political support. The key reason for that is largely seen in the lack of public acceptance for this technology. The absence of public acceptance, in turn, is in particular due to the environmental risks ascribed to CCS and the adverse effects this technology may create with respect to the development of renewable energy technologies. However, the effects of CCS are manifold and an adequate evaluation of this technology should take into account relevant aspects as comprehensively as possible. Since sustainability indicators are not the only ones stakeholders are interested in, attention also has to be paid to further indicators. By means of a multi-criteria analysis considering different scenarios, we investigate the consequences of the application of CCS in Germany that may serve as an alternative to an extension in the use of renewable energies. In doing so, we employ a set of indicators that also include factors distinct from sustainably indicators. The results show that there is a broad range of factors causing the future of CCS in the German power sector to look gloomy.

## 1. Introduction

Due to the entry into force of the Paris Agreement on the 4th of November 2016 the search for and the application of effective greenhouse-gas abatement policies and technologies may get a new push. In this context, already known but controversial technologies might take an active role in helping to reach ambitious targets like the 1.5 °C-target. The focus of this study is on the social, environmental and economic impacts of the application of CCS, representing such a controversial technology. We examine whether the cancellation of CCS projects could be justified or not given the different impacts.

The extension of the use of renewable energies is another option to pursue the international climate protection goals. That is why we compare a CCS deployment scenario with a scenario envisaging a high share of renewables. Within this paper, we will determine the impacts of the considered scenarios on social, environmental and economic factors.

Social, environmental and economic impacts of the use of individual technologies have been analyzed in many studies. Yet, there are research gaps in the context of related impact assessments in complex systems (see e.g., [1,2]). Varun [3], Elghali et al. [4], Dombi et al. [5], and Hofer et al. [6] for example, analyzed the impacts of selected renewable energy technologies by using up to 20 indicators. A larger number of technologies is assessed e.g. by [7–9] and [1]. In principle, an increase in the number of considered technologies does not have to result in a reduction of indicators. Roth [7], for example, analyzed 18 technologies using 75 different indicators.

Onat/Bayer [10], Chen et al. [11] and Munksgaard [12] analyzed

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energy technologies within the external-cost framework. Complex energy systems comprising different technologies have been assessed by Santoyo-Castelazo/Azapagic [2] Diakoulaki/Karangelis [13], Raugei/Leccisi [14] and Baležentis/Streimikiene [15].

Generally, the selection of the indicators is based on their relevance for the assessment of sustainable development (see e.g., [8,2]). In order to minimize both complexity and effort, the number of indicators is usually limited to 10 to 20 (see e.g., [1,2]). With respect to the dimensions of sustainability the indicators are generally ordered into the categories "economic", "environmental" and "social". Economic and environmental indicators are usually quantifiable whereas for the assessment of social aspects mainly qualitative indicators are used. Differences in units as well as differences in the characteristics of the indicators hamper their aggregation, which, however, is necessary for an overall assessment as well as for a comparison of different sets of technologies. Thus, an assessment of social aspects often remains more or less disregarded (see e.g., [16,3]).

Using a broad range of various indicators in combination with a multi-criteria approach we show how impacts of diverging energy systems can be compared. The selection of indicators is not limited to sustainability indicators. In doing so, we strive to obtain a better understanding of the various interests of stakeholders. Based on social, environmental as well as economic factors, we assess advantages and disadvantages of different pathways of an electricity supply system. Beside changes in the installed capacity we consider variations in the production as well as alterations in electricity imports and exports.

The paper is organized as follows: In Section 2 we provide a short overview of the recent developments regarding CCS. In Section 3 we describe the approach we applied for the assessment of the different scenarios. Results are presented and discussed in Section 4. Section 5 concludes.

## 2. Recent developments regarding CCS

Already before the Paris Agreement entered into force, CCS has been regarded – for several reasons – as a promising option to slow global warming (see e.g., [17,18]). The IEA [19] describes CCS as a key greenhouse gas abatement option in the 450-ppm scenario that is supposed to be largely consistent with meeting the international '2 °C-target'. Among the advantages of the CCS technology frequently stressed (see [20]) is that research findings for conventional fuels can still be employed and investment costs for new infrastructures – like electricity grids – required for the use of backstop technologies, e.g. solar energy technologies, can be reduced. Furthermore, it may improve security of energy supply, as coal and storage capacity for $CO_2$ are available on a large scale [21]. The European Parliament and the Council assume that 15% of the $CO_2$ reductions required in the EU in 2030 could be attained by the use of CCS [22]. De Coninck et al. [23] found no compelling reasons why CCS technologies could not be widely deployed in the EU in the future.

In Germany, an ambitious energy concept ('Energiekonzept 2050') was launched by the government in September 2010 that integrates national targets for climate protection and energy use. Germany strives for a reduction of greenhouse gases by 80–95% until 2050 (compared to the emission level in 1990), and in addition to and in support of this target, it aims to raise the share of renewable energy in total power generation to at least 80%. The main reason for the presently rapid expansion of renewable energy generation in Germany is the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz) with a priority feed-in, a purchase guarantee and a fixed feed-in tariff for electricity generated by renewable energy technologies.

In Germany, the deployment of CCS therefore tends to take the role of a complement to the renewable energy deployment rather than the role of a substitute. In a joint report of several German federal ministries,[1] CCS deployment is seen as a potentially essential component of a global and national clean fossil fuel strategy [24]. In a report by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Ministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit), there is a call for further research activities on CCS technologies in order to explore their development and cost-reducing potentials and to demonstrate their feasibility in the coming years [25]. In June 2012, the House of the German Parliament (Bundesrat) approved a new CCS law allowing the sub-terrestrial storage of carbon dioxide. However, in July 2012, Peter Altmaier, at that time the acting German Federal Minister for the Environment, Nature Conservation and Nuclear Safety, pointed to the low acceptance of carbon storage by the German population. He argued that CCS could not be implemented in Germany against the will of the population. Political opposition against CCS is raised, e.g. because of its potential health, safety and environmental risks (for such risks see [26]). Some German Federal States (Bundesländer) took a hostile attitude towards CCS deployment and a special clause in the federal law on CCS allows German Federal States to ban the use of CCS in their area which some of them finally did. Therefore, it is not a big surprise that there is almost no mention of CCS in the German Climate Action Plan 2050 [27] adopted in 2016. Yet, the German government will launch a research and development program addressing industrial $CO_2$ recycling (carbon capture and utilization, CCU). It is only briefly stated that – if additionally necessary – CCS might also play a role in the industrial context. However, although to some extent a related technology, CCU in the industry does not address the abatement of carbon emissions stemming from back-up conventional power plants.

Not only in Germany but all over Europe most CSS-projects in the power sector have been cancelled. Table 1 shows a compilation of CCS projects in Europe that were either cancelled or put on hold. Usually a lack of acceptance has been mentioned as main reason. Financial problems as well as a lack of political support and legal constraints are usually traced back to problems of public perception.

## 3. Methodology

### 3.1. Preliminary remarks

There are several factors – also beyond the purely technical sphere – that influence the attractiveness of CCS use. According to [29,30] in the public eye CCS is generally perceived as an uncertain end-of-pipe technology that will perpetuate fossil-fuel dependence. Concerns about environmental harms from $CO_2$ leaks (e.g. groundwater contamination) boost the negative attitude towards CCS [31]. In many studies it is highlighted that there is in general little knowledge about CCS in the public (see e.g., [32,33]). Moreover, a lack of trust in CCS stakeholders enhances the perception of risks [34] and generally less attention is paid to opportunities and possible benefits e.g. for the local economy (see e.g., [30,34]).

Oltra et al. [35] stress that rising political opposition against CCS e.g. of non-governmental organizations and experts might induce an increase in the costs associated with CCS use. Political opposition might be raised from advocacies of alternative technologies. Environmentalists and renewable-energy lobbyists are concerned about the competition between CCS and renewable-energy technologies for R&D funds and they are concerned that CCS could raise the level of investments in large centralized power plants, which tend to reinforce present supply structures with adverse effects on energy saving efforts [36]. Thus, CCS is frequently seen in a competitive and not in a complementary way. In Germany, for example, where there have been strong public efforts to support renewable energy alternatives, the renewable energy sector has much to lose. Costs of renewable energy

[1] These ministries are the German Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the Federal Ministry of Education and Research.

**Table 1**
CCS Projects in Europe on hold/canceled.

| CCS-Project | | | | Official reason for cancelling | | | | |
|---|---|---|---|---|---|---|---|---|
| Project name | Leader | | Size | Economics | Legal issues | Support by politics | Others | Reason in detail |
| Goldenbergwerk | RWE | DE | 450 MW | | x | | | Lack of German Carbon Storage Law (KSpG) |
| Jänschwalde | Vattenfall | DE | 250 MW | | x | | x | Environmental fears and lack of legal framework |
| Compostilla | ENDESA | ES | 323 MW | | | | | n.a. |
| FINNCAP | Fortum | FI | 565 MW | | | | x | Abandoned due to company strategy |
| Porto Tolle | ENEL | IT | 250 MW | | | | x | Environmental reason, complaints from green groups/local industry |
| Green hydrogen | Air Liquide | NL | 0.55 Mt/yr | | | x | | Dutch gov. was unable to confirm the co-funding of €90 million |
| Eemshaven | Essent | NL | 1,600 MW | | | x | | Dutch gov. decided to support Green Hydrogen instead |
| Barendrecht | Shell | NL | 0.4 Mt/Yr | | x | x | | Local opposition about $CO_2$ storage |
| ROAD | E.ON | NL | 250 MW | x | | | | Project team waits for financing |
| Magnum | Nuon | NL | 1200 MW | x | x | | | Dutch law caused additional problems with where to store the $CO_2$ |
| Kårstø | Naturkraft | NO | 420 MW | x | | | | No grants to continue the process on Kårstø |
| Halten | Statoil | NO | 860 MW | x | | x | | Poor profitability of the power plant even without carbon capture |
| Zeng Risavika | CO2 Norway | NO | 50 MW | | | | | n.a. |
| Belchatow | PGE | PL | 260 MW | x | | | | Lack of funding |
| Getica | Turceni Energy | RO | 330 MW | x | | | | Sponsors seek funding to enable the work to progress |
| Longannet | E.ON UK | UK | 300 MW | x | | | | Focus on other projects with the £1bn funding |
| Hunterston | Ayrshire Power | UK | 1,600 MW | x | | | x | Economic slowdown and funding uncertainty for the move |
| Teesside low carb. | Progressive | UK | 400 MW | x | | | x | No funds available |
| Killingholme | C.GEN | UK | 470 MW | x | | | x | Construction of gas-fired power plant instead |
| Petershead | Shell and SSE | UK | 385 MW | x | | | | UK £1bn CCS Competition was cancelled before it was to be awarded. |
| White rose | Capture Power | UK | 426 MW | x | | | | |
| Don valley power project | Sargas | UK | 900 MW | x | x | | | Dept. for Business, Energy and Industrial Strategy refused development grant for $CO_2$ pipeline, extension of EEPR grant was declined |

*Source:* Ref. [28], updated by IEK-STE.

technologies were declining in recent years and due to this favorable cost development and rising financial loads of the German feed-in tariff system, Germany is modifying its support scheme. Competition for available public funds might become fiercer and opposition of renewable-energy groups against CCS may rise.

On the technical side, there are several research studies investigating – amongst other things – the effectiveness of CCS, the costs of CCS use and profitability of divergent CCS technologies. According to the IPCC [26], with available CCS technologies about 85–95% of the $CO_2$ in a plant can be captured. Each step of CCS (separation, compression, transport, and storage) necessitates energy input which therefore is not available for other consumptive activities and which is called the 'energy penalty' of CCS. The lower bound for the energy penalty for post-combustion CCS from pulverized-coal fired power plants is about 11%, but a decent target value might be about 29% [37]. Implementation of CCS in large coal-fired power plants represents the lowest cost option in the electricity sector at around USD 35/t$CO_2$ to USD 50/t$CO_2$ avoided, while due to the lower initial specific carbon content in natural gas, carbon capture from gas-fired plants involves avoidance cost within a range of USD 53/t$CO_2$ to USD 66/t$CO_2$ avoided [38].

Crucial for the deployment of CCS is its attractiveness particularly for investors. There are several recent studies analyzing the investors' sphere of CCS. Abadie & Chamorro [39] investigate the negative influence of uncertainty on CCS investments. Middleton et al. [40,41] analyze different sources of uncertainty such as geologic uncertainty. Middleton et al. [41] present a model for optimizing the capture, transport and storage of $CO_2$. Rübbelke & Vögele [42] apply load dispatch models in their investigation of the effects of CCS use on the surpluses of electricity suppliers. Abadie et al. [43] evaluate two divergent CCS technologies applied in coal-fired power plants from investors' point of view.

We will next consider different aspects of the deployment of CCS and renewables in Germany. This will shed some light on how well-founded arguments in the political discussion are that incite the political opposition against CCS and renewables. Possible impacts of these technologies are assessed by using a set of indicators. For getting a comprehensive picture economic, environmental as well as social aspects are taken into account. Against the background of transforming existing energy systems into sustainable ones, a countless number of indicators have been developed (see e.g. [44]). The list contains social factors (e.g. "share of household income spent on fuel and electricity"), economic factors (e.g. "fuel shares in energy and electricity", "energy import dependency"), and environmental factors (e.g. "GHG emissions from energy production", "air pollutant emissions from energy systems"). In order to restrict the complexity we select 25 indicators for our analysis. The selection is based on the relevance of the factors for stakeholders in Germany. Since stakeholders are interested in different aspects, besides indicators which are directly linked to sustainable development (e.g. $CO_2$ emissions, use of coal), we take additional relevant indicators such as producer and consumer rents as well as different kinds of public perceptions into account.

In the following, we apply a four-stage approach: In the first stage, we select and present indicators, which reflect different views on the electricity system. In a next step, we develop scenarios for the electricity system in Europe of the year 2030. Employing a dispatch model in combination with data of Enso-E on installed capacities and assuming different paths for prices for $CO_2$-allowances we calculate figures for electricity production in Germany. In the third stage, we link the indicators with the data on installed capacities and electricity production. For being able to compare scenarios appropriately we normalize the indicators using a min-max approach and compile the results in a performance matrix. Using weighting factors we calculate composite indicators in the fourth stage. These indicators compress the results and provide information for stakeholders taking into account different points of views (Table 2).

**Table 2**
Overview methodical framework.

| Step 1: Selection of indicators taking perspectives of different actors into consideration | Step 2: Specification of scenarios for electricity supply and demand in Europe (based on scenarios of by ENTSO-E) | Step 3: Assessment of the indicators for the electricity system | Step 4: Compressing results |
|---|---|---|---|
| Selection of indicators focusing on<br>• economic<br>• ecological<br>• social<br>aspects | • Application of a dispatch model for analysis of electricity production in 31 countries in Europe<br>• Calculation of figures on country specific electricity production for scenarios with different assumptions on the development of power plant stocks and prices for $CO_2$ allowances | • Adjustment of the values for the indicators taking installed capacity and electricity production into consideration<br>• Normalization of the values by using min-max approach<br>• Compilation of performance matrix | • Weighing of indicators using weighting factors<br>• Calculation of composite indicators for evaluation of scenarios from view point of different stakeholder |

### 3.2. Impact assessment

#### 3.2.1. Economic impacts

For investors the economic aspects linked with the use of CCS are of particular interest. In our study, we select the following indicators for assessing the economic impacts of CCS:

- net present value (NPV) of the electricity system,
- average levelised cost of electricity (aLCOE) reflecting the specific production cost,
- changes in wholesale prices,
- impacts on producer and consumer rents,
- expenditure for imported fuels, and
- sensitivity to changes in fuel prices/prices for $CO_2$ allowances.

The net present value (*NPV*) reflects the sum of discounted costs during the considered period (including credit for residual value). *NPV* can be calculated for one specific technology as well as for a set of technologies. Eqs. (1) and (2) show the calculation of *NPV* for a single technology and for a set of *k* technologies, respectively [45].

$$NPV_i = \sum_{t=1}^{T} ((Capital_{i,t} + O\,\&\,M_{i,t})\cdot(1+r)^{-t}) + (D_i - Res_i)\cdot(1+r)^{-t} \quad (1)$$

$$NPV = \sum_{i=1}^{k} NPV_i \quad (2)$$

with

| | |
|---|---|
| $T$: | technical lifetime of technology $i$ [–] |
| $Capital_{i,t}$: | total capital construction costs of technique $i$ in year $t$ [EURO] |
| $O\,\&\,M_{i,t}$: | operation and maintenance costs (incl. fuel cost and cost for $CO_2$ allowances) of technique $i$ in year $t$ [EURO] |
| $D_i$: | decommissioning and waste management costs of technique $i$ [EURO] |
| $Res_i$: | credit for residual value of technique $i$ [EURO] |
| $r$: | discount factor [–] |
| $k$: | number of technologies that are in use [–] |

Based on $NPV_i$ for each technology the specific levelised cost of electricity ($LCOE_i$) can be calculated:

$$LCOE_i = \frac{NPV_i}{\sum Elecprod_i\cdot(1+r)^{-t}} \quad (3)$$

with

$Elecprod_i$: amount of electricity produced with technique $i$ [MWh]

The average levelised cost of electricity (aLCOE) corresponds to the weighted sum of $LCOE_i$ in relation to the respective amount of electricity produced.

$$aLCOE = \frac{\sum_{i=1}^{k}(LCOE_i\cdot Elecprod_i)}{\sum_{i=1}^{k} Elecprod_i} \quad (4)$$

Apart from costs, the use of CCS might be linked with changes in revenues resulting from changes in the running costs and achievable prices: depending on the assumed costs for $CO_2$ allowances, the running costs (including fuel costs, costs for $CO_2$ emissions and other variable costs) of coal-fired power plants equipped with CCS can be lower than the respective costs of conventional power plants. In the case of constant prices for electricity, lower costs result in higher producers' surpluses (see e.g. [46]). If coal-power plants are the most costly power plants which are in use, the whole-sale price for electricity and therefore the producer surplus will be affected. If prices drop, the consumer rent reflecting the budget for the consumer that they can spent on non-electricity goods will increase. Thus, consumer and producer surplus as well as changes in prices have to be assessed simultaneously.

In our study we assess the impact of the deployment of power plants equipped with CCS on electricity prices at the spot-market and on consumer and producer surpluses by using a dispatch model. Based on information on the availability of the different types of power plants, the optimal use of the power plant stock is calculated. It is assumed that power plant operators will use their power plants if the short-run marginal costs are lower than or equal to the price for electricity on the wholesale market. Electricity will be imported if the price in other countries is lower than the cost of using additional domestic power plant capacities and if there are import capacities available [47]. The methodological approach is based on the assumption of perfect competition on the electricity market. The price of electricity is determined by the marginal costs of the most expensive power plant needed to cover demand whereat the temporal resolution of the dispatch model applied in this work is one hour. The target function of the optimization formulation is thus:

$$\min Z_t = \sum_n \sum_i c_i\cdot s_{i,n,t}\cdot X_{i,n} + \sum_n \sum_m c_l\cdot imp_{n,m,t} \quad (5)$$

with

| | |
|---|---|
| $t$: | time index [–] and t = {1,2,3 … 8760} |
| $n$, $m$: | country index |
| $i$: | index for power plant type |
| $c_i$: | electricity generation costs of power plant type $i$ [€/MW h] |
| $s_{i,n,t}$: | utilization of power plant type $i$ in country $n$ at time $t$, where $0 \leqslant s_{i,n,t} \leqslant 1$ [–] |
| $X_{i,n}$: | installed capacity of power plant type $i$ in country $n$ [MW] |
| $c_l$: | costs for exchange of electricity [€/MW h] |
| $imp_{n,m,t}$: | net imports of electricity from country $n$ to country $m$ [MW h] |

A secondary condition is that demand must always be covered.

$$\sum_i s_{i,n,t}\cdot X_{i,n} + \sum_m imp_{n,m,t} \geqslant d_{n,t} \quad \forall\ n \quad (6)$$

$d_{n,t}$: electricity demand in country $n$ at time $t$ [MWh]

In addition, electricity import and export capacities must be considered.

$$imp_{n,m,t} \leqslant NTC_{n,m} \quad \forall\ (n,m) \tag{7}$$

with

$NTC_{n,m}$: net transfer capacity between countries $n$ and $m$ [MW].

The expenditure on import of fuels is calculated based on the costs for fuel and the import quotas.

$$Exp = \sum_{i=1}^{l} \left( \frac{Electrprod_i}{\eta_i} \cdot \frac{3.6}{calvalue_i} \cdot P_i \cdot imp_i \right) \tag{8}$$

with

| | |
|---|---|
| Exp: | expenditure on import of fuels [Euro] |
| $\eta_i$: | efficiency of power plant i [%] |
| $cal_value_i$: | calorific value of coal used in power plant i [MJ/kg] |
| $P_i$: | price for fuel used in power plant i [Euro/kg] |
| $imp_i$: | import quota for fuel used in power plant i [–] |

For assessing the sensitivity of the results to changes in costs we used the indicators “sensitivity to changes in fuel prices” and “sensitivity to changes in the prices for $CO_2$ allowances”. These indicators show how the average levelized costs of electricity will change if the price for fuel or the price for $CO_2$ allowances is modified.

### 3.2.2. Ecological impacts

A main objective of using CCS is the reduction of $CO_2$ emissions. The $CO_2$ emissions of CCS power plants as well as the emissions of other power plants can be calculated by:

$$CO2 = \sum_{i=1}^{k} \left( \frac{CO2fuel_i * Electrprod_i}{\eta_i} * (1 - \mathrm{CO2captrate}_i) \right) \tag{9}$$

with

| | |
|---|---|
| *CO2*: | amount of $CO_2$ emitted to the atmosphere [kg] caused by the electricity sector |
| $CO2_fuel_i$: | fuel specific $CO_2$ emission factor of by power plant *i* [kg/kW h] |
| $CO2captrate_i$: | share of $CO_2$ emissions of power plant *i* that is captured and stored [%] |

Beside $CO_2$, there are many other ecological and technological indicators, which could also be reasonably taken into account for assessing CCS. Examples are: cumulative energy demand (CED), global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) or summer smog, and terrestrial ecotoxicity (TETP) potentials. Usually life cycle assessment (LCA) approaches are used for the assessment of these factors (see e.g., [48,49]).

Not all parameters mentioned above are available for every generation plant considered within this study. Thus, in order to provide a conclusive comparison of the considered electricity generation technologies with regard to their environmental and technological impacts, we focus our argumentation on indicators, which have been published by official institutions for each technology. Accordingly, we ignore indicators, which have been analyzed only for a selected number of technologies.

Taking electricity production into account the overall induced effects by LCA-category can be calculated as follows:

$$ENV_y = \sum_{i=1}^{k} mLCA_{y,i} \cdot Elecprod_i \tag{10}$$

with

| | |
|---|---|
| $ENV_y$: | total sum of environmental impact *y* linked with the use of power plant fleet [kg] |
| $LCA_{y,i}$: | specific factor of environmental/technological impact *y* for power plant *i* [kg/kWh] or [TJ/kWh] |

As indicator for the impacts on resource demand we chose the demand for coal as input for power plants: reductions in the efficiencies of the coal-fired power plants will result in higher specific demand for coal. The need for coal can be assessed by

$$Coal = \sum_{i=1}^{l} \left( \frac{Electrprod_i}{\eta_i} \cdot \frac{3.6}{calvalue_i} \right) \tag{11}$$

with

| | |
|---|---|
| Coal: | specific coal demand for coal-fired power plant i [kg] |
| $cal_value_i$: | calorific value of coal used in coal-fired power plant i [MJ/kg] |

### 3.2.3. Social aspects

In many studies public perception of transport and storage of $CO_2$ are highlighted as main factors for the deployment of CCS (see e.g., [50–52]). Usually, these surveys focus on the sources of the captured $CO_2$, the means of transport and the $CO_2$ storage formation whereas the link between perception and the amount of $CO_2$ that is captured and stored is not considered.

Not only CCS but also coal in general, lignite opencast mines, as well as renewables are affected by perception problems (Table 3). Since the problems cannot be assigned to one single category of perception without neglecting perception problems other energy technologies are confronted with, we apply an assessment scheme developed by [53].

In order to take differences between scenarios into account, we weighted the perception indicators with the technology specific capacity that is installed in the corresponding scenario.

Sometimes the attitude and perception of CEOs and political decision-makers differ from the public perception. For taking the views of CEOs and political decisions-makers on selected aspects into consideration we include “expected impact on the energy system from the viewpoint of CEOs and political decision-makers” and “uncertainties the impact is linked with” as indicators (Fig. 1). These indicators were introduced by World Energy Council (WEC) and have been continuously used for the assessment of the viewpoints of CEOs, ministers and experts from across the globe on factors, the energy sector is faced with (see e.g., [54]). According to WEC, renewable energies as well as energy efficiency are considered to be technology fields with high impacts on the energy sector. Since these technologies are linked with high uncertainties, WEC includes these technology fields to the ones “that keep energy leaders busy at work”.

In contrast to renewable energies, the expected impact of CCS has significantly declined in the recent years. The drop in the impact has been linked with an increase in the uncertainties associated with CCS. Currently, CCS is considered to be of minor importance and a technology that needs further investigation.

In order to elaborate differences between the scenarios we employ the factors “expected impact on the energy system from the viewpoint of CEOs and political decisions-makers” and “uncertainties the impact is linked with” and weight them with the installed capacity.

## 3.3. Multi-criteria approach and composite indicator

For being able to compare scenarios, it is necessary to condense the information the individual indicators provide. Since a scenario assessment can also be interpreted as a multi-criteria problem, a multi-criteria

**Table 3**
Perception of technologies.

| Technology / Perception Category | Coal | CCS | Natural Gas | Nuclear | Wind ON | Wind OFF | PV | Solar Heat | Biomass | Efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.Trust | -1 | -1 | | -1 | 1 | | -1/1 | -1 | -1/0 | -1 |
| 2. National Economics | 0/1 | -1 | 0/1 | -1/0 | 1 | -1/0 | -1/0 | 0/1 | 1 | 1 |
| 3. Individual Economics | | | | -1 | | | -1 | | | |
| 4. Environment | -1 | 0/1 | 1 | 0 | -1 | 1 | 0 | 0 | -1/0 | -1/0 |
| 5. Social & Ethics | -1 | -1 | | -1 | | | 1 | 0/1 | | 1 |
| 6. Techn. Feasibility | | 0 | 1 | -1 | 0 | | 0 | 0 | | |
| 7. Health | -1 | | | 0 | -1 | | | | | |
| 8. NIMBY | -1 | -1 | | -1 | 0/1 | 1 | | 1 | | |
| 9. Potential of Disaster | | 0 | | -1/0 | | | 1 | | | |

*Source:* Own compilation based on [53].

decision assessment (MCDA) approach can be applied (see e.g., [55,56]). Multi-criteria assessment approaches have been widely used for the assessment of technologies as well as for the assessment of scenarios reflecting the development of sectors or regions (see e.g., [16,15,57,13,58]). With respect to the application of indicators, they can be categorized in (i) value measurement, (ii) goal, aspiration and reference-level and (iii) outranking models (see e.g., [59]). In value measurement models, numerical scores are calculated for each scenario whereas the scores are calculated based on the values the indicators are assigned with. In the "goal", "aspiration" and "reference-level" models the differences to desirable levels of performance are measured and summed up for each scenario. The outranking models are based on a pairwise comparison of the indicators.

In the following we will apply a value measurement approach calculating a composite indicator as numerical score of the corresponding scenario. The 25 indicators selected in our study have different units and are not directly applicable for assessment. Thus, based on the indicator set, the chosen assessment approach needs three subsequent steps:

- normalization of results: enables a methodologically reliable comparison of indicators with different units,
- weighting of indicators: defines the relative importance of indicators based on a normative foundation or value concept, which has to be made transparent,
- aggregation: final assessment by aggregation to a composite indicator, while an interpretation of sophisticated information by the performance matrix is also possible.

The max-min approach is used to normalize indicators, which yields ranking results between 0 (poor performance) and 1 (best performance). For example, lower emissions, lower costs or higher acceptance lead to higher performance. The normalized indicators are calculated by setting the difference between the value of indicator ($x_k$) in the selected scenario and the smallest values of the indicator ($x_{min}$) in all scenarios in proportion to the difference between the greatest ($x_{max}$) and smallest values.

$$u(x_k) = \frac{x_k - x_{min}}{x_{max} - x_{min}} \quad (12)$$

with

$u(x_k)$: normalized value of indicator $X$ assigned in scenario $k$
$x_k$: value of indicator $X$ in scenario k
$x_{min}$: minimum value of $X$ comparing all scenarios

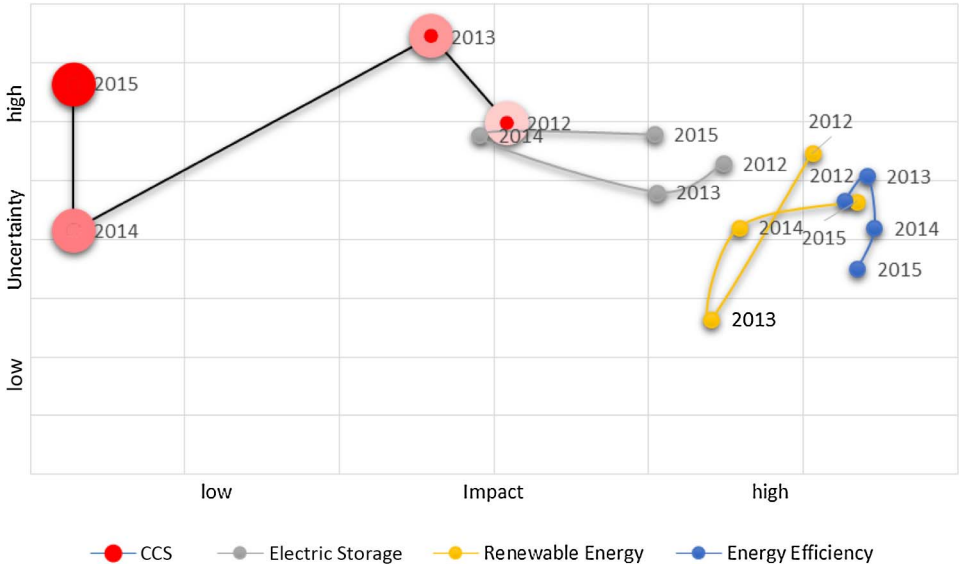


**Fig. 1.** Impact of CCS, renewable energy, energy storage and energy efficiency from the point of view of energy leaders. *Source:* Own compilation based on data of [54] for Europe.

$x_{max}$: maximum value of $X$ comparing all scenarios

With respect to weighting, four different approaches are selected, where (1) allows for substitution of indicators across all pillars and (2)–(4) only consider one pillar. Weighting factors define the relative strength of indicators, with a possible consideration of partial substitution (or compensation). A weighting factor equal to zero defines an indicator to be irrelevant. The following weighting approaches are chosen:

(1) equal weighting of all indicators, which in the case of a different number of indicators per pillar implicitly results in unequal weighting of pillars
(2) environment indicators only, assigning zero weight to economic and social indicators
(3) economic indicators only, assigning zero weight to ecological and social indicators
(4) social indicators only, assigning zero weight to ecological and economic indicators.

A multi-attribute value method for aggregating the individual indicators in the form of a weighted sum is used, consistent with the OECD approach for technology evaluations [60,61] and already demonstrated for CCS assessment (see e.g., [62]). It combines individual indices to form an overall index.

$$I = \sum_{i=1}^{n} w_i \cdot u(x_i) \tag{13}$$

with

$i$: impact factor, with $i = [1,25]$,
$w_i$: weighting factor for indicator $I$, *with* $\sum w_i = 1; 0 \leqslant w_i \leqslant 1$.

## 4. Scenario assessment

### 4.1. Scenario Specification

Six scenarios have been selected for analyzing the possible impacts of deploying CCS in Germany. In the reference scenario ('REF') it is assumed that CCS power plants will not reach market maturity for the next 20 years in Europe. Regarding the installed capacity of wind and PV power plants we assume an increase in capacity to 74 GW (Wind) and 57 GW (PV), respectively.

For the 'CCS' scenario we anticipate that CCS power plants will be ready for the market in 2030. We assume that in Germany new coal-fired plants will be equipped with CCS. In this scenario the capacity of hard coal-fired power plants equipped with CCS will be 11 GW whereas the capacity of lignite-fired power plants with CCS will reach 3 GW. The installed capacity of wind and PV will be the same as in the 'REF' scenario (see Fig. 2).

The third scenario 'REG' is based on the assumption that instead of CCS an increase in the use of renewables is selected as the primary measure to reduce $CO_2$ emissions. Accordingly, the installed capacity of wind and PV will be significantly higher than in the REF and CCS scenarios: The installed capacity will increase to 101 GW (corresponding to a share of 38% on the overall installed capacity) and to 61 GW for PV.

In order to outline the impacts of high prices for $CO_2$ allowances on the results, three additional scenarios are implemented. In these scenarios ('REF_high', 'CCS_high' and 'REG_high') we assume an increase in $CO_2$ certificate prices to 93 \$/t$CO_2$. The development of the capacities are equivalent to the respective scenario with a moderate increase of prices for $CO_2$ allowances.

As mentioned above, for the calculation of economic impacts, data on capital, and operation and maintenance costs (incl. fuel cost and cost for $CO_2$ allowances) is needed. The data used for these calculations originates from IEA [63] whereas the prices for fuel and $CO_2$ allowances are adjusted to the scenarios of Entso-E [64], since Entso-E provides more detailed information on the development of the electricity market in Europe (incl. data on net transfer capacities and changes in installed capacities on country level). In principle, all scenarios are based on the same cost figures. Only the price for $CO_2$-allowances differs between the scenarios: For the scenarios 'REF', CCS' and 'REG' a price of 31 \$/t$CO_2$ for $CO_2$ allowances is assumed. For 'REF_high', CCS_high' and 'REG_high' the price is 93 \$/t$CO_2$ (Table 4).

A combination of Entso-E and EURELECTRIC has been chosen as main source for the scenarios because extensive information on power plants (installed capacity, fuel consumption) and electricity demand (e.g. information on peak and base load) is published by Entso-E and EURELECTRIC for each country in Europe. Other studies on CCS (e.g., [66,67,36,68–70]) provide this information only on an aggregated level.

29 countries in Europe and 40 different kinds of power plant technologies are taken into account. Using data on existing power plant stocks and stock extensions provided by EURELECTRIC we draw inferences on power plant efficiencies and ascertain power-plant specific production cost by taking into account fuel prices [71,72]. In agreement with ZEP, we assume that greenfield CCS-coal fired power plants will have efficiency losses of 8% points relative to conventional coal-fired power plants; retrofitted power plants are assumed to involve efficiency losses up to 12% points [65] (Table 5).

For the assessment of the environmental impacts resulting from technological pathways, we use official data provided by the German environmental protection agency "Umweltbundesamt" [73] and IEAGHG [74] for different kinds of power plants located in Germany.[2] The data provided in the database of the Umweltbundesamt and in a study of IEAGHG includes information on the environmental and technological impacts related to the utilization of the power plants, to impacts related to the construction of the plants as well as on environmental impacts of upstream chains (see [73,74]). The database of the Umweltbundesamt ("probas") and IEAGHG reference to sources containing background information (e.g. on system boundaries or tools used for the assessment of the emissions and impacts). However, in the references the methods applied for the calculation of these values are incompletely documented. Thus, it is not possible to retrace the calculations of the impacts to their full extent. Despite the limitations on the documentation, the data of probas and IEAGHG has been continuously used by different stakeholders and for policy guidance. Since we intend to assess scenarios from the viewpoint of different actors this compelled us to use this data, too (being aware of the fact, that the data provided in those databases might be flawed).

The database and the IEAGHG publication contain information on power plants put into operation in the years 2005, 2020 and 2030. Using interpolations for the periods between these years we linked this information with data on the vintage structure of the power plant stock. The numbers being provided in probas and IEAGHG represent emissions and impacts related to the production of 1 TJ or 1 kWh electricity. We standardized the numbers by using for all specific factors kWh as reference (see Table 6 for examples of the standardized factors).

The direct $CO_2$-emissions of the electricity supply system are assessed by using default emission factors provided by [73] in combination with efficiency parameters and the calculated electricity production. For the assessment of social aspects we use the data presented in Table 3 and Fig. 1 (values for 2015).

Table 7 summarizes the assumptions on weighting factors for the chosen variants:

[2] Since the data provided by [73] and IEAGHG [74] is based on scenarios, which differ partially from the ones considered in this study, the numbers used for our calculations should be used carefully and only in an indicative way.

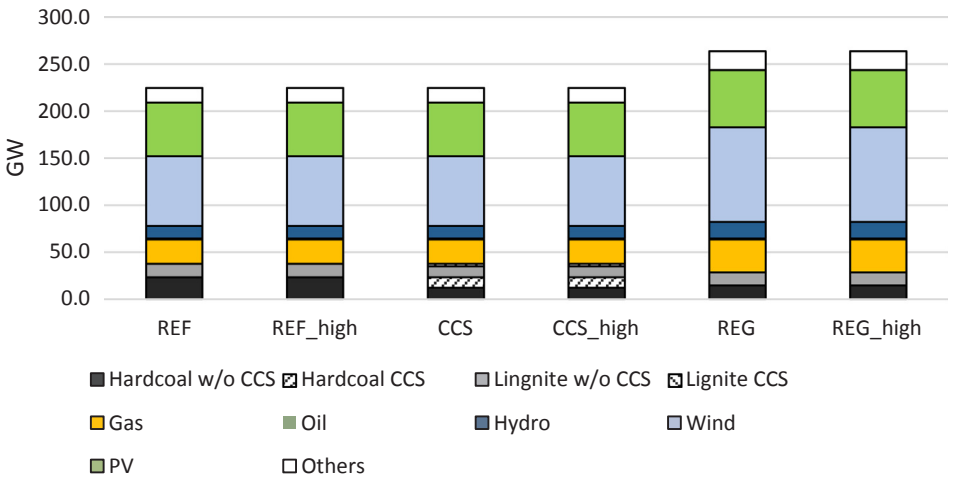


**Fig. 2.** Assumed capacity in Germany (2030). *Source:* Own compilation based on [64].

**Table 4**
Assumed economic parameters.

| | | | REF | CCS | REG | REF_high | CCS_high | REG_high |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ prices[a] | | €/ton | | 31 | | | 93 | |
| Fuel costs[a] | | | | | | | | |
| Hard coal | | Euro/GJ | | | | 3.48 | | |
| Lignite | | Euro/GJ | | | | 0.44 | | |
| Natural gas | | Euro/GJ | | | | 10.28 | | |
| Oil | | Euro/GJ | | | | 23.2 | | |
| Technology specific cost | | | | | | | | |
| Coal-fired power plants | Capital cost[b] | Euro/kW | | | 1500 (hard coal), 1700 (lignite) | | | |
| | O&M (w/o fuel cost)[c] | Euro/MWh | | | 4 (hard coal), 6 (lignite) | | | |
| | Lifetime | Years | | | | 30 | | |
| CCS power plants | Capital cost[b] | Euro/kW | | | 2500 (hard coal) −2700 (lignite) | | | |
| | O&M (w/o fuel cost)[c] | Euro/MWh | | | | 6 | | |
| | Lifetime | | | | | 30 | | |
| Gas-fired power plants | Capital cost[b] | Euro/kW | | | | 750 | | |
| | O&M (w/o fuel cost)[c] | Euro/MWh | | | | 3 | | |
| | Lifetime | | | | | 15 | | |
| Nuclear power plants | Capital cost[b] | Euro/kW | | | | 4800 | | |
| | O&M (w/o fuel cost) | Euro/MWh | | | | 0.7 | | |
| | Lifetime | | | | | 40 | | |
| Wind power plants | Capital cost[b] | Euro/kW | | | | 2500 | | |
| | O&M (w/o fuel cost) | Euro/MWh | | | | 7 | | |
| | Lifetime | | | | | 15 | | |
| PV power plants | Capital cost[b] | Euro/kW | | | | 1400 | | |
| | O&M (w/o fuel cost) | Euro/MWh | | | | 0 | | |
| | Lifetime | | | | | 15 | | |
| Others | Capital cost[b] | Euro/kW | | | | 1700 | | |
| | O&M (w/o fuel cost) | Euro/MWh | | | | 7 | | |
| | Lifetime | | | | | 30 | | |
| Interest rate | | % | | | | 5 | | |

Remarks: Capital Cost: overnight capital costs, O&M: operation and maintenance cost (without fuel cost), Lifetime: time period for which investors expect to received a return on their investment.
[a] Ref. [64].
[b] Ref. [63].
[c] Ref. [65].

- Variant 1 assigns equal weighting factors to each of the 25 indicators: 1/25 to each.
- In Variant 2 the weighting factors are 1/8 for economy and 0 for the other indicators.
- Variant 3 has a weighting factor of 1/8 for ecology and 0 for the other indicators.
- In Variant 4 the weighting factors are 1/9 for social indicators and 0 for the others.

Variant 1 reflects the view of a stakeholder who rates all factors equally. In Variant 2 it is assumed that only economic factors count. In Variant 3 economic and social factors are neglected whereas in Variant 4 the stakeholder is only interest in social aspects.

### 4.2. Results

#### 4.2.1. Performance

The scenarios are based on different assumptions on costs and available capacity. Thus, the scenarios differ with respect to the electricity production. In the reference scenario coal-fired electricity production will have a share of more than 45% in the overall electricity production. In the CCS-scenario 18% of the electricity will be produced by using power plants equipped with CCS. In REG, wind power stations will become dominant with respect to the electricity supply.

**Table 5**
Assumptions on efficiencies and resulting marginal cost (2030).

| | Efficiency[a] (gross) | Resulting short run marginal cost (incl. fuel costs and penalty of 31 Euro/t $CO_2$ assumed for emitting $CO_2$) |
|---|---|---|
| | % | Euro/MWh |
| Hard coal w/o CCS | 38–49 | 44–56 |
| Hard coal with CCS | 35–41 | 33–38 |
| Lignite w/o CCS | 36–47 | 39–50 |
| Lignite with CCS | 33–39 | 22–26 |
| Natural gas w/o CCS | 46–66 | 57–81 |
| Natural gas with CCS | 50–55 | 64–68 |
| Nuclear | 33 | 15.9 |
| Oil | 34–43 | 151–175 |
| Renewables | 100 | 1 |

*Sources:* Refs. [63,65], own calculations based on [71].
[a] Values depend on vintage structure of power plant.

In the scenarios with high prices for $CO_2$-allowances (REF_high, CCS_high and REG_high) coal will only be used in exceptional cases. Instead, gas-fired power plants will be employed to a larger extent. The assumed increases in the prices for $CO_2$-allowances will reinforce the trade of electricity within Europe. Accordingly, in the scenario REF_high more electricity will be imported. Since CCS-power plants will be less affected by the increases in prices for $CO_2$-allowances in the scenarios CCS_high the changes in domestic production will decrease less than in the REF_high scenario. Table 8 shows the results for the economic impacts calculated by using the data provided in Table 4.

In the CCS scenario the cost of the installed electricity system, calculated as net present value, is about 2% higher than in reference scenario. The scenarios REG, CCS_high and REG_high show even higher costs. In the scenario REF_high the net present value of the electricity system is lower due to decreases in the use of coal-fired power plants. The increases in the cost of the REG and REG_high scenarios are mainly caused by increases in the overall installed capacity.

In the case of a carbon allowance price of 31 Euro/t $CO_2$, as assumed in REF, CCS and REG scenario, the running costs of CCS power plants will be lower than the ones of power plants without CCS (even if the decreases in efficiency are taken into account). The resulting high utilization rates of the CCS power plants mean that the additional investment costs will result in only small increases in the aLCOE. Since wind and solar power plants are restricted in their utilization because of restrictions on the availability of wind and solar radiation, for the REG-scenario aLCOE will increase significantly. In the scenarios with higher prices for $CO_2$-allowances the difference between CCS_high and REF_high as well as between REG_high and REF_high will be more significant.

Taking into consideration that the price for electricity on the

**Table 6**
Environmental and technological parameters.

| | Emissions | | | | | | Impacts | | | | | | | | | CED | | | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $SO_2$ g/kWh | | | $NO_x$ g/kWh | | | GWP $kgCO_2$-eq./$kWh_{el}$ | | | EP $gPO_4$-eq /$kWh_{el}$ | | | AP $gSO_2$-eq/$kWh_{el}$ | | | MJ/kWh | | | |
| | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | 2010 | 2020 | 2030 | |
| Hard coal (w/o CCS) | 0.59 | 0.29 | 0.28 | 0.80 | 0.71 | 0.60 | 0.89 | 0.78 | 0.76 | 0.10 | 0.09 | 0.08 | 1.18 | 0.79 | 0.70 | 9.02 | 7.85 | 7.67 | [73] |
| Hard coal (CCS[a]) | | 0.16 | 0.15 | | 0.90 | 0.76 | | 0.20 | 0.20 | | 0.14 | 0.12 | | 0.94 | 0.83 | | 10.4 | 10.2 | [74][b] |
| Lignite (w/o CCS) | 0.63 | 0.42 | 0.40 | 0.36 | 0.35 | 0.33 | 0.95 | 0.93 | 0.91 | 0.05 | 0.05 | 0.05 | 0.88 | 0.67 | 0.64 | 8.55 | 8.19 | 7.83 | [73] |
| Lignite (CCS[a]) | | 0.23 | 0.22 | | 0.47 | 0.45 | | 0.17 | 0.16 | | 0.08 | 0.09 | | 0.78 | 0.75 | | 11.3 | 10.8 | [74][b] |
| Gas | 0.01 | 0.01 | 0.01 | 0.56 | 0.46 | 0.34 | 0.41 | 0.34 | 0.31 | 0.07 | 0.06 | 0.04 | 0.40 | 0.33 | 0.24 | 6.96 | 5.81 | 5.38 | [73] |
| PV | 0.07 | 0.07 | 0.07 | 0.08 | 0.08 | 0.08 | 0.06 | 0.06 | 0.06 | 0.01 | 0.01 | 0.01 | 0.14 | 0.14 | 0.14 | 5.00 | 5.00 | 5.00 | [73] |
| Wind | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 3.69 | 3.69 | 3.69 | [73] |
| Other | 0.28 | 0.28 | 0.28 | 0.60 | 0.60 | 0.60 | 0.76 | 0.76 | 0.76 | 0.08 | 0.08 | 0.08 | 0.70 | 0.70 | 0.70 | 7.67 | 7.67 | 7.67 | [73] |

[a] Values for power plants using post-combustion technology.
[b] For reason of comparability, information on changes in comparison to power plant without CCS is used instead of absolute values proved in [74].

**Table 7**
Indicator weighting.

| Indicator weights in categories | Number of indicators | Variant 1: Equal weight | Variant 2: Econ. only | Variant 3: Ecol. only | Variant 4: Soc. only |
|---|---|---|---|---|---|
| Economy | 8 | 1/25 | 1/8 | 0 | 0 |
| Environment | 8 | 1/25 | 0 | 1/8 | 0 |
| Social | 9 | 1/25 | 0 | 0 | 1/9 |
| Total | 25 | 1 | 1 | 1 | 1 |

*Source:* Own compilation.

**Table 8**
Results "Economic impacts"

| | | | Changes in comparison to REF | | | Changes in comparison to REF_high | |
|---|---|---|---|---|---|---|---|
| | | | CCS | REG | REF_high | CCS_high | REG_high |
| (A1) | Net present value (NPV) of the electricity system | % | 2.1% | 10.6% | 1.1% | 4.1% | 8.0% |
| (A2) | Average levelised cost of electricity (aLOCE) | % | 0.1% | 14.2% | 37.2% | −11.6% | 4.4% |
| (A3) | Wholesale prices | % | −0.6% | −9.9% | 62.8% | −11.9% | −1.9% |
| (A4) | Annual producer surplus | % | 10.1% | 1.3% | 42.2% | 5.5% | 24.4% |
| (A5) | Consumer surplus | % | −0.6% | −9.9% | 20.0% | −1.9% | −11.9% |
| (A6) | Expenditure on import for fuels | % | 20.2% | −57.7% | −6.7% | 62.4% | −35.4% |
| (A7) | Sensitivity to changes in fuel prices | % | 16.1% | −57.2% | −14.5% | 54.7% | −41.4% |
| (A8) | Sensitivity to changes in prices for $CO_2$ allowances | % | –33.0% | −41.6% | 30.7% | −31.3% | −61.6% |

*Source:* Own calculation.

wholesale market is mainly determined by the running cost of power plants and not by their investment costs, in the CCS scenario as well as in the REG scenario more 'cheap' electricity production capacity is available. Thus, the slope of the merit order curve will differ drastically between the scenarios. On the wholesale market the cost of the most expensive power plant which provides electricity for the domestic market, irrespective of whether it is used domestically or abroad, determines the wholesale price. The substitution of conventional coal-fired power plants by CCS power plants of the same capacity will influence the wholesale price only in a very limited way because the coal-fired power plants in the REF scenario and the CCS power plants in the CCS scenario will be used at similar utilization rates: looking at the annual average wholesale price, a drop by 1.3% can be observed. On average, the reduction in wholesale prices for the REG scenario is stronger than for the CCS scenario. However, in this scenario the wholesale prices will fluctuate quite strongly.

As mentioned above, the producer surplus reflects the difference between profits and running cost. While decreases in electricity prices lower electricity producers' surpluses, these surpluses rise with increasing electricity sales and with decreasing production cost. For the CCS scenario we ascertain an increase in producers' surplus by 5% resulting mainly from lower production costs in combination with small decreases in wholesale prices. In REG there will be a significant drop in producer surpluses, mainly resulting from decreases in wholesale prices and in domestic electricity production.

Besides effects on the net profits of producers, also rents of consumers – and thus their welfare – will be affected by the changes in prices. Consumer rents can be determined by multiplying changes in electricity prices by consumers' electricity consumption levels. In the CCS scenario the drop in electricity prices by 1.3% will result in an increase of the consumer rent by 437 million Euro. Assuming that the consumers will benefit from the changes in the prices on the wholesale market and ignoring changes in feed-in tariffs in the REG scenario the consumer rent will raise by more than 3,400 million Euro. In the REG scenario, the expenditures for imports of fuels will decrease significantly. In REG_high more gas will be used in the electricity sector. Thus, in this scenario more money will have to be spent on importing this fuel. Since gas is more expensive than coal in total the expenditures for imports will increase.

Table 9 shows changes of environmentally relevant emissions and technological parameters for the scenarios under consideration. Since this paper aims to introduce a multi-criteria approach considering a variety of indicators, the environmental and technological impacts will only be briefly discussed with regard to changes of the selected indicators. As expected, in the scenarios CCS and REG the (direct) $CO_2$ emissions will be significantly lower. In the CCS scenario, $CO_2$ emissions will be reduced by 31.2% and in the REG by 33.6%. An increase in prices for $CO_2$ allowances will result in a significant reduction in the use of coal-fired power plants and thus in a soaring reduction of $CO_2$ emissions. However, the decrease of $CO_2$ emissions for the scenarios with high $CO_2$ prices is only partly linked to structural changes in electricity generation. As can be observed in Fig. 3, these scenarios show a decrease in overall national electricity generation in comparison to those scenarios with a low $CO_2$ price.

**Table 9**
Results "Ecological impacts"

| | | Changes in comparison to REF | | | Changes in comparison to REF_high | |
|---|---|---|---|---|---|---|
| | | CCS | REG | REF_high | CCS_high | REG_high |
| (B1) | $CO_2$ | −31.2% | –33.6% | −62.6% | −36.3% | −66.6% |
| (B2) | $SO_2$ | −11.5% | −29.0% | −72.3% | 8.9% | −62.8% |
| (B3) | $NO_x$ | 13.7% | −30.8% | −59.1% | 78.1% | −47.3% |
| (B4) | GWP | −27.0% | −31.6% | −62.2% | −27.1% | −60.5% |
| (B5) | EP | 23.7% | −30.6% | −59.1% | 102.7% | −46.7% |
| (B6) | AP | 9.0% | −29.8% | −66.2% | 74.6% | −54.0% |
| (B7) | CED | 12.7% | −14.8% | −41.5% | 45.3% | −13.7% |
| (B8) | Demand for coal | 16.3% | −24.5% | −68.0% | 89.3% | −73.2% |

*Source:* Own calculation.

Similar results can be observed for the GWP. This indicator combines climate change relevant emissions such as methane, nitrous oxide, methane, or sulfur hexafluoride and expresses them as $CO_2$ equivalents. While the development of GWP for the scenarios CCS and REG are quite close, analogous to the $CO_2$ emissions, REF_high shows a significant drop in GWP of 62.6%.

Since the technical process of extracting $CO_2$ emissions requires $SO_2$ to be removed simultaneously, the results for $SO_2$ are similar to the ones for $CO_2$ and GWP: Significant reductions occur in the CCS and REG scenario and even greater ones in the REF_high scenario. As discussed before, the application of CCS technology will lead to a reduction in overall efficiency of coal fired power plants. Consequently, emissions of particulate matter or $NO_X$ arising from the use of coal in power generation will increase. As a result, the CCS scenario shows an increase of 13.7% in $NO_X$ emissions in comparison to REF. Although $NO_X$ emissions for gas fired power plants are considerably higher than for coal fired power plants, with a stronger use of renewables in REG the overall $NO_X$ emissions can be reduced significantly. Thus, for global environmental impacts like $CO_2$ concentration or GWP, the implementation of CCS results in comparable mitigation levels as the application of renewable energy sources. On the other hand, on a local scale an increased utilization of CCS will partially lead to higher environmental pollution. Therefore, the implementation of CCS is linked to a trade-off between local and global environmental impacts (see [75]). Similar problems arise concerning the eutrophication and acidification potential. Due to higher consumption of coal, emissions of pollutants with a significant effect on EP and AP, like phosphate, ammonia, or $NO_X$ will increase as well. Thus, our calculations show an increase in EP of 23.7% for the CCS scenario compared to REF. A significant drop by 30.6% in the EP can be identified for REG and a decrease of 59.1% for REF_high where coal will be used only on a restricted basis. Regarding the acidification potential the scenarios show larger divergences. With an increased share of renewables in electricity production and a drop in the use of coal the AP will drop by 29.8% for REG and 66.2% for REF_high, respectively. The cumulated energy demand is closely linked to the efficiency of the corresponding power plant technology. Taking into account an energy penalty for CCS and a reduction in the use of conventional power plants in the REG and REG_high scenarios, the increase of the CED in the CCS scenario and the decrease in the REG and REF_high scenarios become reasonable. As argued before in Section 4.1, we estimate the efficiency of coal-fired power plants with CCS to be 8–12% lower than the efficiency of coal-fired power plants without CCS [see [65]]. Therefore, although the share of coal for power generation in REG and CCS are approximately equal, CCS implies a strong increase in coal demand. This trend is significantly stronger for CCS_high. Due to the high price for $CO_2$ emissions, the utilization of coal-fired power plants without CCS is very limited. Thus, the efficiency losses of CCS power plants in combination with a high utilization of coal-fired power plants lead to an increased coal demand of 89.3% in comparison to the REF_high scenario. In the REG and REG_high scenarios coal-fired power plants will be either replaced by PV and wind power plants or will be used less than in the reference scenario. Consequently, demand for coal will drop significantly in these scenarios.

Using information on perceptions regarding different technologies we assessed social impacts. In a first step, we sum up the data on the different technologies presented in Table 3 using technology specific capacity as weighting factor (Table 10). Regarding the category "Trust", which includes e.g. the trust in the owners of the power plants the REG scenarios show the highest degree of positive perception. Concerns about the economics of power plants equipped with CCS result in a negative figure for the category "Economics" in the CCS scenario. The

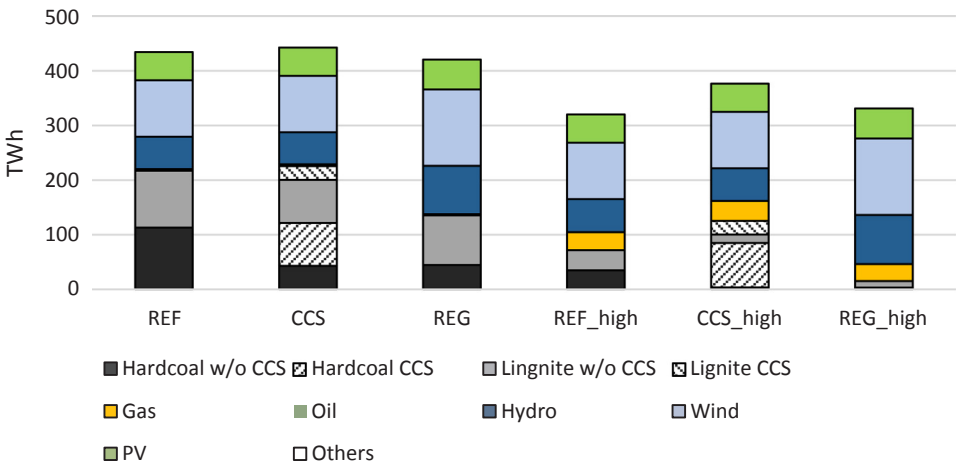


**Fig. 3.** Electricity Production in Germany (2030). *Source:* Own calculation.

REG scenario has advantages with respect to "Social & Ethics" aspects taking into account e.g. working conditions in the mining sector.

The category "Health" includes impacts on air, noise and water pollutions. Since in the public especially the impacts of wind power are discussed controversially, the REG scenario is characterized by a negative perception. A similar interpretation applies to scenarios dominated by the use of coal. In the REG-scenario the "Not In My Back Yard" (NIMBY)-effect is less important than in the other scenarios because the decentralized technologies PV and wind are more accepted in the public.

Regarding the expected impact on the energy system from the viewpoint of CEOs and political decision-makers the REG and the REG_high scenarios show the highest values. CCS represents the scenario with the highest uncertainties with regard to its impacts. These results correspond to the assessment of economic and ecological indicators (Table 11).

#### 4.2.2. Composite indicator

Based on the performance matrix and the approaches for normalization and weighting, different results can be considered and compared (Fig. 4):

- Equal weighting: clear advantage for REG compared to REF and CCS. Surprisingly, CCS shows a slight improvement of all three considered aspects compared to the reference scenario.
- Econ. only: considering exclusively economic aspects, REG is the most attractive option. This is mainly due to the indicators wholesale price, (avoided) import expenditure, and sensitivity to fuel prices and certificate prices. CCS represents the second best option. Especially the sensitivity to changes in $CO_2$ prices and the NPV of the electricity system show a significant improvement compared to REF.
- Ecol. only: for ecological impacts REG shows the strongest divergence. Although the utilization of CCS allows for a drastic decrease in GWP and $CO_2$ emissions, an increase in local pollutions (except for $SO_2$) offsets those emission reductions to a certain degree. Thus, the CCS scenario shows only a slight advantage compared to the reference scenario.
- Soc. only: considerable advantage of REG compared to CCS and REF. For perceived health and environmental aspects, CCS has a weak advantage in comparison to the reference scenario.

In total, the results are rather robust, given the assumptions and the set of indicators. REG performs best for all for variants considered, while the CCS scenario represents the second best option. For the analysis of high $CO_2$ prices similar conclusions can be derived: in all four alternatives the scenario REG prevails.

Furthermore, the general structure does not seem to be affected by high $CO_2$ prices, with one exception: the variant "Ecol only" for high $CO_2$ prices shows a higher performance of REF in comparison to CCS. Although CCS_high leads to a strong decrease in $CO_2$ emissions and GWP compared to REF_high, due to a more frequent utilization of coal fired power plants, emissions of other pollutants increase drastically.

Choice and weighting of indicators have a crucial effect on the results. On the one hand the findings of the assessment are strongly relating to the calculated indicator results, but on the other hand the results are strongly affected by normative consideration and corresponding weightings.

## 5. Conclusions

Germany's private households face rising electricity prices as the costs of the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz) are passed forward to consumers in the form of surcharges. The same holds for those companies not belonging to the energy-intensive industries in Germany that benefit from lower wholesale

**Table 10**
Results "Social impacts".

| | | | REF | CCS | REG | REF_high | CCS_high | REG_high |
|---|---|---|---|---|---|---|---|---|
| Perception | (C1) | Trust | 7.6 | 7.6 | 35.5 | 7.6 | 7.6 | 35.5 |
| | (C2) | Economics | −57.2 | −57.2 | −51.8 | −57.2 | −57.2 | −51.8 |
| | (C3) | Environment | −3.3 | 17.3 | 14.5 | −3.3 | 17.3 | 14.5 |
| | (C4) | Social & Ethics | 19.4 | 19.4 | 27.3 | 19.4 | 19.4 | 27.3 |
| | (C5) | Techn. feasibility | 25.9 | 25.9 | 29.9 | 25.9 | 25.9 | 29.9 |
| | (C6) | Health | −111.9 | −98.1 | −110.4 | −111.9 | −98.1 | −110.4 |
| | (C7) | NIMBY | 26.3 | 26.3 | 49.0 | 26.3 | 26.3 | 49.0 |
| | (C8) | Impact | 100 | 100 | 103 | 100 | 100 | 103 |
| | (C9) | Uncertainty | 100 | 115 | 103 | 100 | 115 | 103 |

*Source:* Own calculation.

**Table 11**
Performance matrix.

| | | Indicators | REF | CCS | REG | REF_ high | CCS_ high | REG_ high |
|---|---|---|---|---|---|---|---|---|
| Economy | A1 | Net present value | best | | worst | | | worst |
| | A2 | Average LCOE | best | | worst | | | worst |
| | A3 | Wholesale price | worst | | best | worst | best | |
| | A4 | Producer surplus | worst | best | | worst | | best |
| | A5 | Consumer surplus | worst | | best | worst | | best |
| | A6 | Exp. on imported fuels | | worst | best | | worst | best |
| | A7 | Sensitivity to fuel prices | | worst | best | | worst | best |
| | A8 | Sensitivity to $CO_2$ certificate prices | worst | | best | worst | | best |
| Ecology | B1 | Direct $CO_2$ | worst | | best | worst | | best |
| | B2 | $SO_2$ | worst | | best | worst | | best |
| | B3 | NOx | | worst | best | | worst | best |
| | B4 | Cumulated energy demand | | worst | best | | worst | best |
| | B5 | Coal demand | | worst | best | | worst | best |
| | B6 | Global warming potential | worst | | best | worst | | best |
| | B7 | Eutrophication potential | | worst | best | | worst | best |
| | B8 | Acidification potential | | worst | best | | worst | best |
| Society | C1 | Pecept.-Trust | | worst | best | | worst | best |
| | C2 | Pecept.-Economics | | worst | best | | worst | best |
| | C3 | Pecept.-Environment | worst | best | | worst | best | |
| | C4 | Pecept.-Social & Ethics | | worst | best | | worst | best |
| | C5 | Pecept.-Technological feasibility | | worst | best | | worst | best |
| | C6 | Pecept.-Health | worst | best | | worst | | best |
| | C7 | NIMBY | | worst | best | | worst | best |
| | C8 | Impact on the energy system | | worst | best | | worst | best |
| | C9 | Uncertainties the impacts are linked with | best | worst | | best | worst | |

best value
worst value

*Source:* Own compilation.

electricity prices as they are largely exempted from contributing to the costs of the Renewable Energy Sources Act scheme. At the same time, Germany restricts its room for manoeuvre by banning or restricting the use of some technological options (i.e. nuclear power or CCS). Reasons for such public policies are largely public concerns and political opposition against these technologies.

Traditionally, technology assessments are mainly based on techno-economic considerations. However, presently it is mainly a lack of public acceptance that is making a case for the missing support for CCS in Germany in the political debate. The paper presents a methodology for technology assessment enabling to incorporate different actors' perspectives. The novelty is based on the one hand on the selection of indicators which span economic, environmental and social aspects but also reflect different actors' perspectives. Especially the differentiation between producers and consumers and respective rents goes far beyond 'simple' cost considerations. On the other hand, also the introduction of weighting factors for indicators as part of the multi-criteria approach reflects actors' perspectives, ranging from a balanced acknowledgement of all indicators to specific foci on either economic, environmental or social indicators only, neglecting the perspectives of respective other societal groups. Since the stakeholders are not only interested in sustainability indicators, we extended the list of indicators by taking factors like "producer rent" and "expected impacts on the energy system from viewpoint of CEOs and political decisions-makers" into consideration and assessed the overall electricity system.

Generally, the use of an indicator set reflecting different societal perspectives enables to a better understanding of the foundations and dynamics of controversial public discussions about energy technologies. Decision-makers have to decide on the selection of technologies being a part of their strategies. In the case of CCS the set of decision-makers comprises utilities deciding upon investments in R&D facilities or in generation capacities and politicians which have to decide whether CCS may be an option within the governmental strategy and whether and how to support technology R&D and deployment. Also societal groups not directly involved in R&D or investment decision-making but contributing to public discussion can use the results of this study for a better understanding of other perspectives.

The comparison of different scenarios shows disadvantages for electricity supply systems where coal-fired power plants equipped with CCS technology are used with respect to 1) the overall cost of the electricity supply system (measure as sum of net present values) and 2) the sensitivity of the cost to changes in the prices for $CO_2$-allowances. The higher demand for coal (resulting e.g. from decreases in the net efficiencies of power plants if they are equipped with CCS) does not only increase the expenditures for imports of coal but also support increases in ecological impacts. Particularly, the eutrophication and acidification potential will be significantly higher than in the scenario with more extensive use of renewables. Regarding social aspects the differences the CCS scenario shows fewer disadvantages. With respect to this category of indicators we identify disadvantages for CCS i.e. for "Nimby" and uncertainties about technological feasibility.

We find that the large-scale deployment of the CCS technology in Germany would be less beneficial for both consumers and producers than many of the earlier studies suggest. Particularly interesting is the

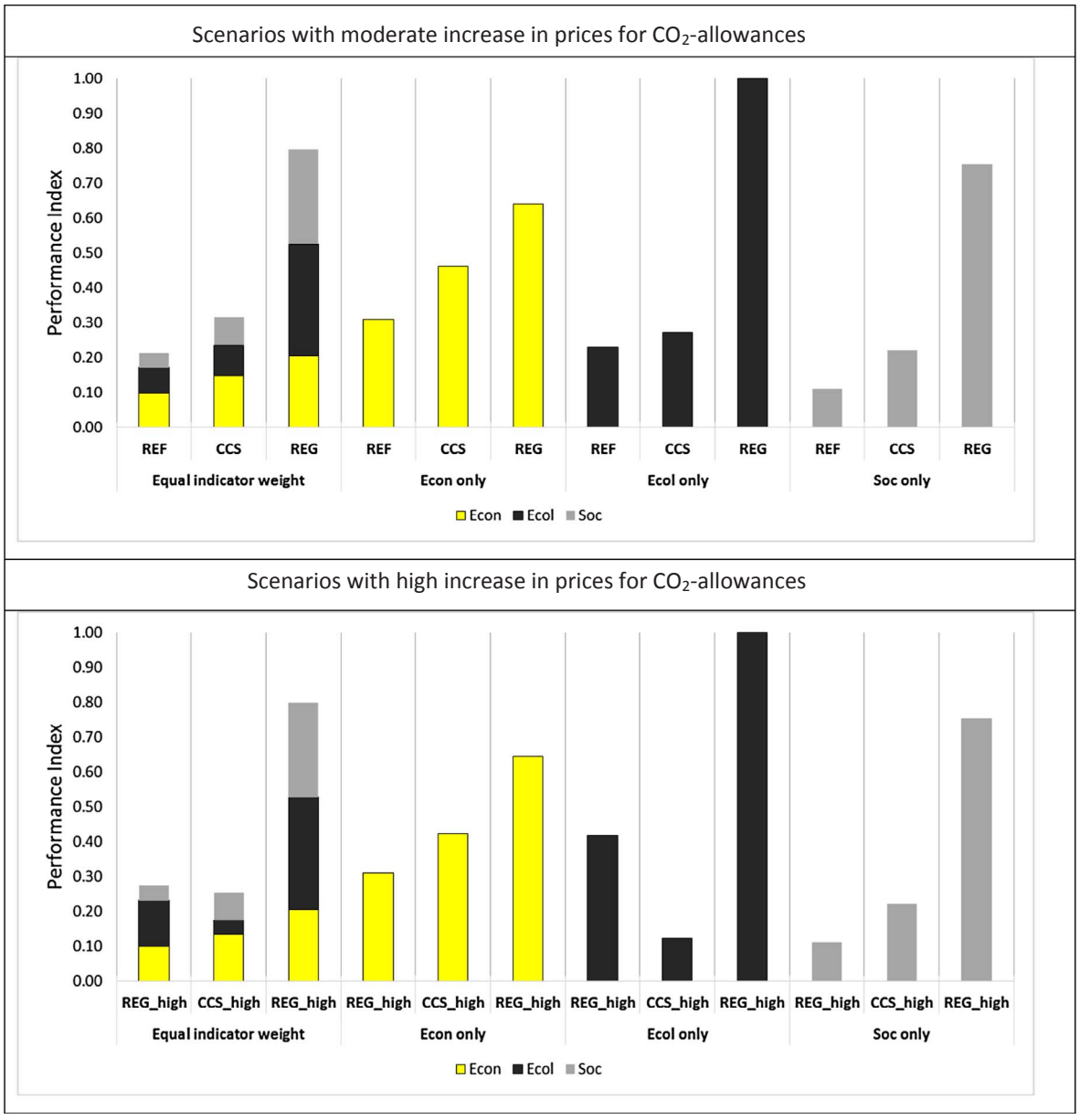


**Fig. 4.** Composite indicator results. *Source:* Own calculation.

interplay between the welfare effects on consumers and producers and the public acceptance of the CCS technology. On the one hand, positive effects on consumers' welfare tend to mitigate political opposition against the application of this technology. And the rise in electricity suppliers' profits could cover suppliers' additional cost of investments necessary to deploy CCS, still leaving a net gain for these companies, also creating a tendency for a positive attitude towards CCS in parts of the company sector.

On the other hand, if nevertheless an adverse public attitude towards CCS remains that possibly triggers governmental regulations limiting CCS, this will have a negative effect companies' willingness to apply CCS. This holds even more, because companies tend to be risk averse concerning radical technology changes (see Rennings et al. [76]). Taking not only public acceptance problems regarding $CO_2$ transport and storage into account but also uncertainties regarding the long-term development of prices on the wholesale market, these influence factors may prohibitive for a large scale deployment of CCS. Therefore, a good chance for a revival of the CCS technology should not be expected under present political conditions.

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